ON THE ESTIMATION OF LONG-WAVE EFFECTIVE RADIATION

By

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INAUGURAL DISSERTATION

WHICH BY DUE PERMISSION
OF THE PHILOSOPHICAL FACULTY OF THE UNIVERSITY
OF UPPSALA WILL BE PUBLICLY DISCUSSED
IN THE PHYSICAL LECTURE THEATRE,
ON 2 APRIL 1955 AT 10 O'CLOCK,
FOR THE DEGREE OF DOCTOR
OF PHILOSOPHY

BY

OLOV LÖNNQVIST
FIL. LIC., SÖDERM.NER.

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On the estimation of long-wave effective radiation

This paper is intended to recapitulate the research completed and the results obtained in the following six papers on the estimation of effective radiation.

A. "A general method and a simplified formula for calculating effective radiation." (*Arkiv för geofysik 1*, 4, pp. 79–115, 1950.)

B. "Calculating effective radiation with due regard to its diffuse nature." (*Arkiv för geofysik 1*, 15, pp. 441–451, 1951.)

C. "On the effective radiation to various parts of a cloudless sky." (*Tellus 3*, 3, pp. 148–153, 1951.)

D. "Theoretical verification of the logarithmic formula for the relative net radiation to a cloudless sky." (*Arkiv för geofysik 2*, 8, pp. 151–159, 1954.)

E. "Synthetic formulae for estimating effective radiation to a cloudless sky and their usefulness in comparing various estimation procedures." (*Arkiv för geofysik 2*, 12, pp. 245–294, 1954.)

F. "Measurements of effective radiation at Bromma airport simultaneous with radiosoundings." (*Arkiv för geofysik 2*, 15, pp. 371–376, 1955.)

SUMMARY OF THE RESEARCH COMPLETED

1. The general method

The method which I have termed the general method is a numerical method for estimating effective radiation. The problem involved was to find a useful numerical technique, accurate though not too complicated. This item was studied in (A) and (B).

In (A) the radiation was assumed to be purely vertical. The atmosphere was divided into horizontal layers. It was shown that five layers are enough in most cases. The long-wave spectrum of water-vapour was divided into nine wave-bands. The computation was carried out for each wave-band by the aid of a simple computation scheme in which the radiation was followed from the top of the atmosphere down to the earth's surface. The method can be used for both cloudy and clear skies. It can also be modified so as to apply to estimating upward radiation.

In (B) I paid regard to the diffuse nature of the radiation. Using the logarithmic formula discussed below and valid for parallel radiation, I showed by the aid of an integration over the whole hemisphere that the "diffusing" factor which must be used

when treating the diffuse radiation as being vertical takes a value around 1.65. It varies slightly with the temperature lapse-rate in the lowest few kilometres of the atmosphere.

2. *Synthetic formulae*

By a synthetic formula is meant by me a formula which represents a series of estimated data in a similar way to that in which an empirical formula represents observed data. It was found appropriate in (A) to use a logarithmic form for the formula. This formula was slightly modified in (B) after considering the effects of the diffuse nature of the radiation. The final logarithmic formula reads

$$r = A + Bt_0 + C(1 + \varkappa)\gamma_m - D \ln \varkappa \varrho_0,$$

where r is the relative net radiation to a cloudless sky, expressed as a percentage; t_0 is the surface temperature, γ_m is the temperature lapse-rate up to 2 km, $\varkappa$ depends on the relative distribution of humidity in the vertical, and ϱ_0 is the absolute humidity at surface. The form of the formula and the constants A, B, C and D were determined by the aid of the general method by studying 86 type-atmospheres. It was pointed out that the logarithmic formula cannot be used for extremely high or extremely low values of the optical depth $\varkappa \varrho_0$.

In (E) two other synthetic formulae were introduced. They were found by use of the logarithmic formula. The *linear* formula expresses the effective radition as a linear function of t_0, γ_m, $\varkappa$ and U_0, where U_0 is the relative humidity at surface. The *illustrative* formula, on the other hand, expresses the effective radiation as a function of t_0 and U_0, the lapse-rates of t and U in the lowest two kilometres of the atmosphere, and the atmospheric pressure, the last quantity entering as a minor correction to an otherwise linear function.

3. *Theoretical derivation of the logarithmic formula*

In (D) I derived a mathematical expression for the relative net radiation in the case of an isothermal atmosphere. After a rearrangement of the water-vapour spectrum I found it possible to describe the absorption coefficients empirically by a simple exponential function. This device made it possible to treat the transfer problem by mathematical analysis. The logarithmic formula proves to be a useful approximation to the derived expression. The above-mentioned limitations of the logarithmic formula were confirmed. A formula was presented which proves to be useful even for very low and very high values of the optical depth.

4. *Comparison of various estimation procedures*

The numerical values of the constants in the logarithmic formula and in other synthetic formulae depend on which method is used for estimating the effective radiation in the selected type-atmospheres. In (E) I have determined the constants

which correspond to a large number of different estimation procedures, e.g. eight types of radiation charts constructed by various authors. A standard routine, including 25 type-atmospheres, was used for this purpose. By comparing the constants corresponding to different procedures it is possible to compare the practical consequences of the procedures in question.

5. Measurements

Although series of radiation measurements simultaneous with radio soundings have been carried out by some investigators, there are very few series which have been published in detail and which make it possible to compare measured and estimated values of the effective radiation. To increase the number of series I made some measurements of this kind. The results were presented in (F). The instrument used for the radiation measurements was the Ångström pyrgeometer. The special merit of my series of measurements was the use of the best existing device for measuring humidity in the upper air, viz. the rolled hair introduced by Frankenberger.

6. Comparison with empirical data

The sparse occurrence of simultaneous radiosonde and radiation data renders comparison between estimated and empirical data very difficult. In (A) I presented an indirect comparison between radiation data for one year and estimated data based on radio soundings for another year. In addition, a few estimates were compared with radiation data from Alaska under extreme winter conditions.

In (E) a more complete comparison was carried out. The basic data were taken from two papers by Robinson (*Q. J. Roy. Met. Soc.*, 1947, 1950). The measurements by Robinson were compared with estimates obtained by synthetic formulae using sets of constants corresponding to the various estimation procedures mentioned above. It was also possible to use the Robinson data for deriving empirical constants of the synthetic formulae by the method of least squares.

In (F) a comparison was based on my own measurements. As, however, the series of data was short, the derived empirical constants were not conclusive, but the confrontation of the data with various estimation procedures gave an indication of the relative merits of the procedures.

7. The Standard radiation

Already in (A), but above all in (E), I found—for empirical as well as theoretical values of the effective radiation—very large differences of magnitude. To facilitate comparisons of different instruments and various estimation procedures I introduced the concept Standard effective radiation, which was defined as the effective radiation in an ICAO Standard Atmosphere with relative humidity equal to 60 per cent at all heights.

8. The logarithmic formula applied to a related problem

One of the advantages of using a formula instead of a radiation diagram is that the formula renders it possible to derive other formulae for various purposes. This was exemplified in (C), where the logarithmic formula was used to derive a formula for the effective radiation to various parts of a cloudless sky. I found that the empirical formula given by LINKE (*Met. Zeitschr.*, 1931) is a useful approximation to the derived formula, the correction terms being small, at least for small zenith distances.

Using the notation *representative zenith distance* for that zenith distance for which the parallel radiation is equal to the integrated hemispherical radiation, it was shown in the same paper, (C), that the representative zenith distance is almost constant and is equal to about 52 degrees. This has also been found empirically, e.g. by ROBINSON (*loc. cit.*).

CONCLUDING REMARKS

The estimation of long-wave radiation constitutes an important part of the problem of estimating the heat balance of the earth and the temperature changes in the atmosphere. Since routine measurements of long-wave radiation can scarcely be carried out anywhere except close to the earth's surface, the only way to verify procedures for estimating long-wave radiation in the whole atmosphere seems to be to verify effective radiation estimates.

Most of the procedures available for estimating long-wave radiation are graphical. The general method introduced by me is so far the only numerical method which is suitable for use on a routine basis.

The logarithmic formula, the two other synthetic formulae, and the revised Ångström and Brunt formulae, all proposed by me, contain not only surface data for temperature and humidity, as previous formulae do, but also upper air data. They are the only formulae of this kind available for estimating effective radiation.

Provided we use constants obtained empirically or by the aid of the general method or other methods, the comparison of these formulae with other estimation procedures and with empirical data shows that the formulae are of the same quality as the best radiation charts. In addition, I have shown that the formulae have many advantages over the graphical procedures.

Through the research here described I have demonstrated that it is very important to know to what extent carbon dioxide contributes to the downward radiation. ROBINSON's measurements seem to indicate, though not unambiguously, that the contribution is negligible, whereas my own measurements indicate that this contribution would be of the usually assumed magnitude. From ROBINSON's measurements I found a peculiar temperature effect, discussed in fact by ROBINSON himself, which did not come out from any estimation procedure. No effect of this kind was observed

in my own measurements. Provided we assume that the odd temperature effect is due to systematic errors in ROBINSON's measurements, the indication that the carbon-dioxide effect is negligible disappears.

By the aid of the concept Standard radiation I have clearly demonstrated the serious fact that we have a very imperfect knowledge of the magnitude of the effective radiation. At the present time this magnitude cannot be determined with the desired accuracy, either theoretically or empirically.

Finally, I have specified what is needed to increase our possibilities of making good estimates of the long-wave radiation in the atmosphere, viz. comparisons of various radiation instruments, especially as regards their calibration; accurate humidity measurements in the upper air; an increased number of series of simultaneous radiosonde and radiation measurements; and a better knowledge of the absorption spectrum of water-vapour and carbon dioxide with due regard to the variation with temperature of the water-vapour spectrum.

CORRIGENDA

Paper(A)—*Arkiv för geofysik 1*, 4

1) p. 80, ¶ 6, l. 2: rediation *to* radiation
2) p. 85, ¶ 4, l. 1; l. 7: ozon *to* ozone
3) p. 87, Figure 2, text, l. 2: in logarithmic *to* on a logarithmic
4) p. 88, ¶ 3, l. 4; ¶ 5, l. 1: dependency *to* dependence
5) p. 95, ¶ 3, l. 2: ± 0.2 *to* ± 0.1
6) p. 96, Table IX, col. for A; l. 1: ± 0.5 *to* ± 0.3
   l. 2: 49.1 *to* 49.0
   l. 3: ± 0.2 *to* ± 0.1
   l. 4: ± 0.4 *to* ± 0.2
   l. 5: ± 0.4 *to* ± 0.3
   l. 6: ± 0.5 *to* ± 0.4
7) p. 98, Table XI, col. for r: Method *to* Formula; Formula *to* Method
8) p. 99, ¶ 2, l. 7: 13.3 *to* 13.4
9) p. 99, footnotes, l. 1: PHILLIPS *to* PHILIPPS
10) p. 101, footnote: p. 12 *to* p. 87
11) p. 102, Figure 4, text, l. 6: cirkles *to* circles
12) p. 107, ¶ 6, l. 1: emphasise *to* emphasize
13) p. 107, ¶ 7, l. 2; p. 108, ¶ 1, l. 1: Geophysic *to* Geophysik
14) p. 107, ¶ 7, l. 7; l. 18; p. 108, ¶ 1, l. 8; l. 11: Physic *to* Physik
15) p. 108, ¶ 1, l. 10: Phillips *to* Philipps, B.
16) pp. 85–108, throughout: dioxid *to* dioxide

Paper (B)—*Arkiv för geofysik 1*, 15

1) p. 441, ¶ 2, l. 5; p. 445, Fig. 1, text, l. 2: water vapour *to* water-vapour
2) p. 443, ¶ 4, l. 2: *after* unit angle, *add* from a horizontal surface
3) p. 444, ¶ 5, l. 3: 54 *to* 57

4) p. 445, ¶ 1, l. 1: actor *to* factor
5) p. 446, after the first equation, *add* The constants 0.133 and 0.530 are taken from the previous paper (1950), Table C and Table G respectively.
6) p. 447, ¶ 3, l. 7: dependency *to* dependence

Paper (C)—*Tellus 3*, 3

1) p. 148, col. 2, ¶ 2, l. 7: *after z add* , the reference surface being orientated perpendicular to the beam